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Predicting the ignition of crown fuels above a spreading surface fire. Part II: model evaluation

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Abstract. A crown fuel ignition model (CFIM) describing the temperature rise and subsequent ignition of the lower portion of tree crowns above a spreading surface fire was evaluated through a sensitivity analysis, comparison against other models, and testing against experimental fire data. Results indicate that the primary factors influencing crown fuel ignition are those determining the depth of the surface fire burning zone and the vertical distance between the ground/surface fuel strata and the lower boundary of the crown fuel layer. Intrinsic crown fuel properties such as fuel particle surface area-to-volume ratio and foliar moisture content were found to have a minor influence on the process of crown fuel ignition. Comparison of model predictions against data collected in high-intensity experimental fires and predictions from other models gave encouraging results relative to the validity of the model system.

Introduction

The use of models is ubiquitous in fire science. Deterministic approaches aimed at understanding the role that fire plays in the physical and biological environment rely on accurate methods for describing fire behavior. Aside from their use to support fire management decision-making, fire behavior models have been used extensively as research tools (e.g. Clark *et al*. 1996; Fulé *et al*. 2002; Keane *et al*. 2004). Models can contribute to new understanding of natural processes when used as tools to explore the effect of input parameters and intermediate processes within the context of fire behavior and fires effects on the environment.

Besides the safety, operational, and management aspects that often constrain the opportunity to conduct field-based high-intensity fire behavior research (Alexander and Quintilio 1990), the thermal environment of these fires limits the physical characteristics that can be sampled (Clark *et al*. 1999; Butler *et al*. 2004).

Cruz *et al*. (2006) described a model that simulates the ignition of forest crown fuels above a surface fire. The design philosophy of this crown fuel ignition model (CFIM) was to develop a simplified description (albeit one involving some degree of computation) of the processes determining the onset of crowning. A physics-based approach was followed because conceptually it should have broader applicability than empirically based models (e.g. Van Wagner 1977; Cruz *et al*. 2004). The CFIM quantifies the upward energy fluxes originating from a spreading surface fire and in turn calculates both the convective and radiative energy transfer to fuel particles located at the base of the crown fuel layer. The model simplifies the description of certain sub-model components, falling short of describing key fire phenomenology, such as reaction zone processes and flame dynamics. Important flame front parameters needed as intermediate outputs, such as the reaction zone temperature–time profile and flame height, were obtained from simple models. Based on a heat balance equation, CFIM calculates the temperature change over time of fuel particles located at the base of the crown fuel layer as they are heated by upward convective and radiative energy transfer from a surface fire. Fuel particle temperature is used to determine fuel ignition and the consequent onset of crowning fire behavior.

In the present study we evaluate CFIM behavior and prediction capabilities by: (1) analyzing the effect and sensitivity of input and intermediate output variables on the model behavior; (2) assessing its behavior through comparative analysis against other models describing the onset of crowning; and (3) evaluating it against data collected from fire experiments.

Methods

Effect of individual input variables and sub-model outputs

The model response to changes in environmental and fuel complex variables was investigated by analysing the effect of

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Table 1. Baseline values for input/intermediate model output parameters (in bold at center) and variability used in simulations to analyze model behavior

U_{10}, 10-m open wind speed; *MC*, moisture content of fine dead surface fuels; w_a, surface fuel available for flaming combustion; *FSG*, fuel strata gap; *FMC*, foliar moisture content; σ, surface area-to-volume ratio of crown fuel particles; *ROS*, rate of spread; τ_r, reaction time; T_{Fmax}, maximum flame temperature; α_U, wind attenuation coefficient

Parameter	Parameter variability
Input variable	
U_{10} (m s^{-1})	2, 4, **6**, 8, 10
MC (fraction)	0.04, 0.055, **0.07**, 0.085, 0.1
w_a (kg m^{-2})	0.45, 0.65, **0.85**, 1.05, 1.25
FSG (m)	3, 4, **5**, 6, 7
FMC (fraction)	0.8, 1.0, **1.2**, 1.4, 1.6
σ (m^{-2} m^{-3})	3000, 4000, **5000**, 6000, 7000
Intermediate model output	
ROS (m s^{-1})	0.02, 0.05, **0.08**, 0.11, 0.14
τ_r (s)	20, 35, **50**, 65, 80
T_{Fmax} (K)	900, 1000, **1100**, 1200, 1300
α_U	1, 1.5, **2**, 2.5, 3

six variables determining the ignition of crown fuels. They were: 10-m open wind speed (U_{10}), surface fuel available for flaming combustion (w_a), fuel strata gap (*FSG*), moisture content of fine dead surface fuels (*MC*), foliar moisture content (*FMC*), and surface area-to-volume ratio of crown fuel particles (σ). Flaming combustion is assumed to be the fuel consumed in the active combustion zone (Alexander 1982). *FSG* is the vertical distance between the top of the surface fuel strata and the lower limit of the crown fuel layer (Cruz *et al.* 2006). Some of these input variables affect intermediate model outputs, such as the surface fire rate of spread (*ROS*) and the depth of the flaming front. In order to better understand the effect of intermediate variables on the final model behavior, the effect of fire *ROS*, reaction time (τ_r), maximum flame temperature (T_{Fmax}), and wind profile models on surface fire time–temperature (T–T) profile were assessed, and the incident convective and radiative energy fluxes (q_c and q_r, respectively) were also analyzed.

The baseline values (in bold) for the various simulations and the variation in the input parameter being analyzed are presented in Table 1. The parameters were varied within a range expected to be found in both prescribed and wild fires. *ROS* was varied over a range that would represent a moderate- to high-intensity surface fire. Reaction time was also varied over a range expected to occur in light uncompacted to heavy surface fuel beds (Nelson 2003). Surface fire maximum flame temperature was varied from 900 to 1300 K, values characteristic of thin and deep flames observed in wildland fires (Butler *et al.* 2004; Cruz 2004; Taylor *et al.* 2004). The wind attenuation coefficient was varied within the bounds found in field studies for open and closed stands reported by Albini and Baughman (1979).

Table 2. Fuel moisture (fraction) conditions for model comparison (after Rothermel 1991)

Fuel type	Spring	Normal summer	Late summer
1-h	0.09	0.06	0.09
10-h	0.11	0.08	0.04
100-h	0.15	0.10	0.06
Live herbaceous	1.95	1.17	0.70

Comparison with other models

The comparison between models describing the same event provides insight into differences between models, their deficiencies, and limits of applicability. CFIM was compared with predictions from three crown fire initiation models, namely those of Van Wagner (1977), Alexander (1998), and Cruz *et al.* (2004). The four models can be distinguished by how they describe the physical processes determining crown fire initiation. In general, a simpler model, i.e. with less inputs, will be less capable of capturing some of the variation introduced by changes in burning conditions than a more complete model incorporating combustion and energy transfer processes. The different modeling approaches associated with these models constrains the type of comparative analysis that can be undertaken. The threshold for crowning (Scott and Reinhardt 2001) was used to compare model response to burning conditions, as determined by fuel moisture and fuel model. The threshold for crowning is a U_{10}–*FSG* pair conducive to the attainment of: (1) a critical fireline intensity in the Van Wagner (1977) and Alexander (1998) models; (2) a probability of crown fire occurrence of 0.5 in the Cruz *et al.* (2004) model; and (3) a crown fuel particle temperature of 600 K in CFIM. Model comparison was based on the determination of this critical quantity as a function of the two input variables common to all models, U_{10} and *FSG*. To provide a comprehensive comparison between models we evaluated their behavior under three distinct fuel moisture conditions and three distinct surface fuelbeds. The fuel moisture conditions were adapted from Rothermel's (1991) standardized fuel moisture values characteristic of late spring, normal summer, and late summer burning conditions in the Northern Rocky Mountains (Table 2). The current implementation of CFIM relies on Rothermel's (1972) surface fire *ROS* (with modifications by Albini 1976) to estimate the movement of the flaming front. The surface fuelbed characteristics were defined following the fuel model concept (Deeming and Brown 1975). Fuel models NFFL2 (open forest stand with grass and understory as main surface fuels) and NFFL10 (closed forest stand with compacted litter, down woody fuels, and understory) developed in the Northern Forest Fire Laboratory (NFFL) (Albini 1976; Anderson 1982), and a custom fuel model describing a red pine plantation (RPP) (Van Wagner 1968; Cruz *et al.* 2004) were used for the comparison.

Fireline intensity, the energy release rate per unit length of the flame front, is required to estimate the U_{10}–*FSG* threshold for crowning for the Van Wagner (1977) and Alexander (1998) models. It was estimated as:

$$I_B = ROS \cdot w \cdot H_c \quad (1)$$

(Byram 1959), where *ROS* is the surface fire rate of spread ($m\,s^{-1}$), w is the surface fuel consumed ($kg\,m^{-2}$) and H_c is the fuel particle heat content ($kJ\,kg^{-1}$). Following Van Wagner's (1977) original formulation, w is based on the total amount of fuel consumed by the surface fire. In this case, I_B expresses the integrated energy release rate of the fire front per unit length of the fire front (Rothermel 1994). Fireline intensity is also used in CFIM to estimate flame height (Nelson and Adkins 1986) and the initial momentum in the buoyant plume (Nelson 2003). Within this context, the quantity I_B is related solely to the energy released within flaming combustion, and consequently w in Eqn (1) is substituted by w_a, defined as the fuel available for flaming combustion.

The three fuel models were chosen to simulate a broad range of fire characteristics, as defined by potential *ROS*, quantity of fuel consumed in flaming combustion, and total surface fuel consumed. Fuel model NFFL2 is characterized by an uncompacted fuel bed with a moderate fuel load. Of the three fuel models, NFFL2 shows the highest potential for high *ROS*, although the structure of the fuelbed limits the occurrence of high reaction times and the contribution of w_a to the estimation of I_B is small compared to what is found for NFFL10 and RPP. Fuel model NFFL10 has the lowest potential for *ROS* of the fuel models used in the analysis. It was assumed that for the 'late spring' burning conditions only 1-h fuel (fine fuels with $Ø < 6$ mm) contribute to w_a. For the 'normal summer' burning conditions, w_a included all of the 1-h and one-third of the 10-h fuels ($0.6\,mm < Ø < 2.5\,mm$). In the 'late summer' conditions, w_a integrated the 1-h fuels and half of the 10-h fuels. The estimation of w was based on the assumption that all 1-h and 10-h fuels would be consumed in the 'late spring' conditions and all fuels consumed in the summer conditions.

Sensitivity analysis

Sensitivity analysis was applied to quantify the relative impacts of CFIM's main input variables (i.e. U_{10}, w_a, *MC*, and *FSG*) on model output. CFIM outputs analyzed for their sensitivity were: fuel temperature (the maximum attained in the simulation) and intermediate variables determining energy transfer to the fuel particles, namely maximum air temperature in the buoyant plume, convective heat transfer coefficient (maximum), and surface fire upward radiant energy flux (*E*).

The index of sensitivity (*RS*), indicating the proportional response of the model to the changes in the perturbed input parameter, was defined as:

$$RS = \frac{\Delta y}{y_{def} \cdot \Delta_{IV}} \quad (2)$$

Table 3. Range of variables used in sensitivity analysis
U_{10}, 10-m open wind speed; *MC*, moisture content of fine dead surface fuels; *FSG*, fuel strata gap; w_a, surface fuel available for flaming combustion; *FMC*, foliar moisture content; σ, surface area-to-volume ratio of crown fuel particles

Variable	Range
U_{10} ($m\,s^{-1}$)	2–9
1-h time lag fuels *MC* (fraction)	0.04–0.12
FSG (m)	3–8
w_a ($kg\,m^{-2}$)	0.6–1.4
FMC (fraction)	0.8–1.6
σ ($m^{-2}\,m^{-3}$)	3000–7000

$$\Delta y = \frac{\partial y}{\partial x} \cdot \Delta x \quad (3)$$

(Bartlink 1998; Cruz *et al.* 2003), where y *is* the resulting value of the output parameter when the value of the input parameter, x, is perturbed by $\pm 10\%$ (Δ_x), y_{def} is the output parameter under default conditions, and Δ_{IV} is the range of the perturbation (fixed at 0.2).

Absolute *RS* scores less than 1 indicate insensitive (<0.5) or slightly sensitive (0.5–1.0) model responses to inputs, and *RS* scores larger than 1 indicate model sensitivity, which can be divided into moderate (1.0–2.0) and high (>2.0). Given the non-linear nature of the model and the complex interactions between the processes determining fire behavior the sensitivity analysis was carried out by conducting a relatively large number of simulations (200 for each input parameter analyzed) under randomly selected input conditions within a predetermined range (Table 3).

Evaluation against experimental fire data

Results from outdoor fire experiments were compared with CFIM simulations. The experimental fires used in the evaluation exercise included a relatively complete description of the fuel complex and associated burning conditions. The experimental fires were mostly moderate- to high-intensity surface fires (I_B ranged between 457 and 4925 $kW\,m^{-1}$), with some of them exhibiting a limited degree of torching. Table 4 lists the various fires used in the analysis. All fires were from pine stands with a well-defined gap between the surface and canopy fuel layers.

Van Wagner (1968) published the results of nine experimental fires in RPP (*Pinus resinosa*). Four of those fires were used in the present analysis (Table 4), three of them spreading as surface fires and the fourth spreading as a crown fire for less than 1 min. Based on the surface fuel layer description given by Van Wagner (1968), w_a was assumed as $0.9\,kg\,m^{-2}$. This value integrates the litter layer and a fraction (15%) of the duff layer that was assumed to burn within the flaming phase of the fire front. The three operational prescribed fires in maritime pine (*Pinus pinaster*) plantations reported in Burrows *et al.* (1988) were described as having

'...short bursts of crown fire activity...' and being '...just below the threshold for sustaining crown fires' (Alexander 1998: p. 142). Van Loon and Love (1973) described the fire behavior associated with eight prescribed fires in a young slash pine (*Pinus elliotii*) plantation, three of which spread as head fires (Table 4). Plot A2 was described as exhibiting localized crown fire activity, whereas the other two fires (plots A4 and C2) spread as moderate-intensity surface fires. Fernandes *et al*. (2004) report on an experimental fire in a 28-year-old maritime pine plantation block consisting of four distinct fuel complex situations: a plot prescribed burned 13 years before the experiment (RX13), an untreated plot (UN), and two plots prescribed burned 3 and 2 years before (RX3 and RX2, respectively). The experimental fires were accomplished by igniting one side of the block and letting the fire burn successively through the RX13, UN, RX3, and RX2 portions of the block. Both plots RX13 and UN exhibited crowning activity, with 37 and 100% of canopy fuel consumption, respectively. Both these fires were described as burning as passive crown fires, with the ignition of canopy fuels occurring some meters behind the leading edge of the surface fire flame front. RX2 was a low-intensity surface fire and was not used in the analysis.

Stocks *et al*. (2004) and Taylor *et al*. (2004) describe in detail the behavior of various crown fire experiments carried out in jack pine (*Pinus banksiana*) stands near Fort Providence, Northwest Territories, Canada. One of the experimental fires (plot 8) burned partially as a surface fire. After ignition this fire advanced directly down the length of the plot with the prevailing wind. However, after the fire had advanced halfway across the plot, the prevailing winds died off for a period of time and then picked up later on. During the lull in winds, the fire advanced only 30 m for an average spread rate of $0.093\,\mathrm{m\,s^{-1}}$ and it was regarded as 'plot 8b'. This lull in fire activity was noticeable in the post-burn aerial photos taken of the plot (i.e. the scorch activity signifying a surface fire). Surface fuelbed structure was quite distinct from the previous cases analyzed where there was a well-differentiated layer of fine fuels that were assumed to be consumed in flaming combustion. The surface fuelbed of this plot was characterized by a compacted forest floor ($w = 4.6\,\mathrm{kg\,m^{-2}}$) with an average fuel moisture content of 79%. Assuming that 15% of the forest floor layer ($\approx$10 mm depth) and all downed woody surface fine fuels (Ø < 10 mm) were consumed in flaming combustion, w_a was estimated to be $0.77\,\mathrm{kg\,m^{-2}}$. This plot exhibited a dense black spruce understory (Alexander *et al*. 2004; Stocks *et al*. 2004), but its influence on carrying fire vertically into the overstory in this burning period is unknown.

In the absence of a reliable method to estimate *ROS*, the observed surface *ROS* was used as an input for all but the RPP fires (Van Wagner 1968). This ensured that the *ROS* prediction would not introduce error into the analysis. The *ROS* for the RPP fires was predicted through the BEHAVE system with a calibrated custom fuel model (Cruz *et al*. 2004). The remaining fires with some degree of crowning were classified as passive crown fires as per Van Wagner (1977). This suggests that the surface phase controls the overall fire *ROS*, and that the use of the observed *ROS* would not introduce substantial errors in the simulation. The wind-adjustment factor used in the calculations was one that would fit the wind profile observed during the experimental fire. It was estimated by solving the equations defining the wind profile assuming knowledge of the 10-m open and within-stand wind speeds.

Results and discussion

Effect of individual input variables and sub-model outputs

Figure 1 displays the response of crown fuel particle temperature profile to changes in input variables. The 0 in the x-location indicates that the surface fire ignition interface (the flame front leading edge) is directly beneath the crown fuel particle being heated. The model simulation stops when the fuel particle reaches ignition temperature (600 K), hence the truncated profiles. Of the various input variables under analysis, U_{10} (Fig. 1*a*) and w_a (Fig. 1*c*) showed the most effect on the canopy fuel temperature. The strong effect is attributed to the direct relationship between these variables and fireline intensity and flame front depth. Wind speed (U_{10}) affects the energy transfer processes by determining surface fire *ROS*, fireline intensity, depth of the combustion zone, and flame height. The combustion zone defines the depth of the buoyant plume base, which largely determines its strength, and the size of the radiating surface as seen by crown fuels. Flame height determines the z-location of the base of the buoyant plume. Given the same *FSG*, taller flames increase convective heating of the fuel particles. The model suggests that although an increase in U_{10} significantly increases the overall incident energy flux to the canopy fuels, the net energy transfer to the canopy is not necessarily proportional. Higher U_{10} will increase both convective cooling prior to and after the passage of the buoyant plume, and air entrainment in the plume (Alexander 1998). Increases in w_a result in corresponding increases in fireline intensity, flame height, and reaction time, which lead to proportional increases in radiative and convective energy fluxes to the canopy fuels.

FSG and *MC* also showed a strong effect on the model output, albeit lower than U_{10} and w_a (Fig. 1*b*,*d*). *FSG* affects the incident radiative heat flux due to the reduction in the view factor with increased *FSG* and convective energy flux due to air entrainment and consequent cooling of the plume at any height.

MC influences *ROS* and T_{Fmax} and, subsequently, convective and radiative energy transfer processes (discussed below). Decreases in *MC* result in a proportional increase in *ROS*, and consequently in fireline intensity, flame height, flame depth, and buoyant plume strength. A reduction in

Table 4. Experimental fire data used in the evaluation of the crown fire ignition model

T_a, ambient temperature; *RH*, relative humidity; U_{10}, 10-m open wind speed; U_s, within-stand wind speed; *MC*, moisture content of fine dead surface fuels; *FMC*, foliar moisture content; w_a, surface fuel available for flaming combustion; *SH*, stand height; δ, surface fuel bed depth; *FSG*, fuel strata gap; *ROS*, rate of spread; I_B, fireline intensity

Fire name	Stand type	T_a (°C)	*RH* (%)	U_{10} ($m\,s^{-1}$)	U_s ($m\,s^{-1}$)	*MC* (%)	*FMC* (%)	w_a ($kg\,m^{-2}$)	*SH* (m)	δ (m)	*FSG* (m)	*ROS* ($m\,s^{-1}$)	I_B ($kW\,m^{-1}$)	Crowning activity (Y/N)	Source
VW67_R3	Red pine	–	–	3.61	1.65	9	92	0.9	13	0.08	6.92	0.1	2456	N	Van Wagner (1968)
VW67_R4	Red pine	–	–	3.06	0.89	13	100	0.9	13	0.08	6.92	0.025	457	N	Van Wagner (1968)
VW67_R5	Red pine	–	–	1.67	0.76	4	108	0.9	13	0.08	6.92	0.034	899	N	Van Wagner (1968)
VW67_R1	Red pine	24	26	4.16	1.38	10	100	0.9	13	0.08	6.92	0.18	7300	Y	Van Wagner (1968)
BW&B_P1	Maritime pine	21	37	5.56	0.89	9[A]	120	1.2	14	–	2.4	0.05	1104	Y	Burrows *et al.* (1988)
BW&B_P2	Maritime pine	23	33	6.11	0.94	9[A]	120	1.21	14	–	2.4	0.0556	1237	Y	Burrows *et al.* (1988)
BW&B_P3	Maritime pine	25	30	6.67	0.81	9[A]	120	1.18	14	–	2.4	0.0439	953	Y	Burrows *et al.* (1988)
McA66	Radiata pine	21	33	4.5	2.2	12.6	145	1.5	18	–	10	0.066	3875	N	McArthur (1966); Nicholls and Cheney (1974)
VL&L_A2	Slash pine	30.5	50	3.75	1.03	10.2	109	0.87	6.5	–	1.8	0.038	1104	Y	Van Loon and Love (1973)
VL&L_A4	Slash pine	28	71	0.97	0.31	27.8	109	0.76	6.5	–	1.8	0.017	1237	N	Van Loon and Love (1973)
VL&L_C2	Slash pine	30	64	3.75	1.03	17.2	109	0.53	7.7	–	1.8	0.015	953	N	Van Loon and Love (1973)
PF&al_Un	Maritime pine	29	25	5.7	1.89	5	116	1.63	9.1	0.52	4.2	0.060	4925	Y	Fernandes *et al.* (2004)
PF&al_RX13	Maritime pine	29	25	3.2	1.06	5	116	1.54	8.5	0.50	3.5	0.032	1520	Y	Fernandes *et al.* (2004)
PF&al_RX3	Maritime pine	29	25	4.5	1.47	5	116	0.69	10.1	0.31	5.1	0.043	931	N	Fernandes *et al.* (2004)
BS&al_Plot8b	Jack pine	30	26	2.3	0.53	9	93	0.77	10	0.05	3.6	0.093	1107	N	Stocks *et al.* (2004); Taylor *et al.* (2004)

[A]Estimated as per Rothermel (1983).

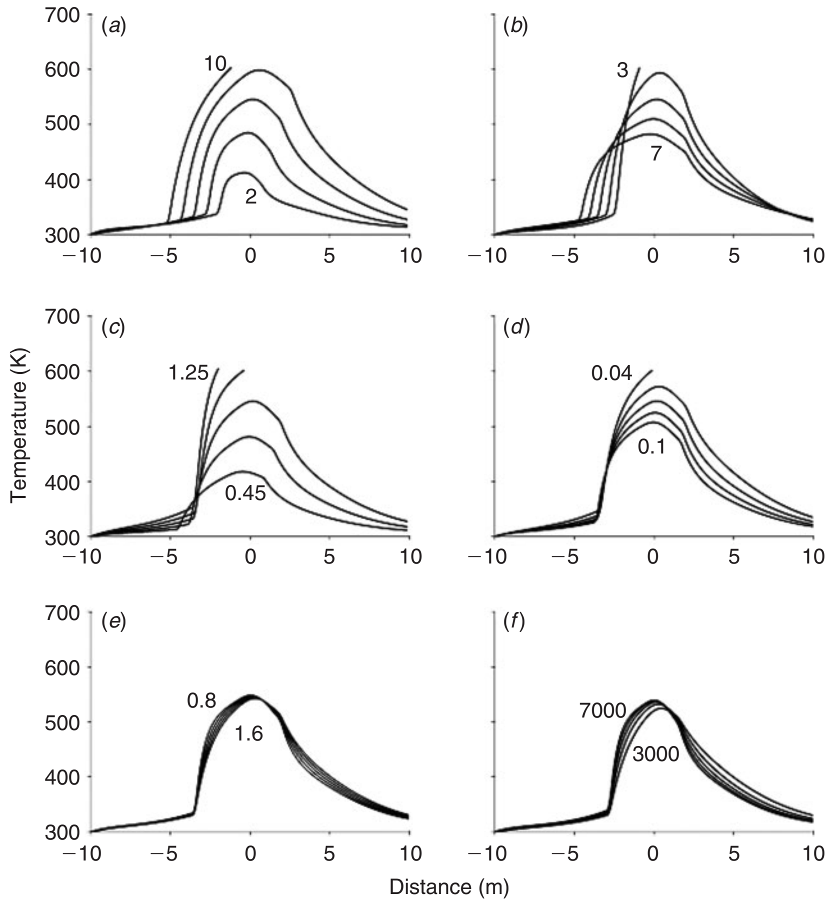

Fig. 1. Predicted temperature of lower canopy fuel particles above a spreading surface fire as a function of various input parameters: (*a*) wind speed (m s^{-1}); (*b*) fuel strata gap (m); (*c*) surface fuel available for flaming combustion (kg m^{-2}); (*d*) surface fuel moisture content (fraction); (*e*) foliar moisture content (fraction); and (*f*) crown fuel particles surface area-to-volume ratio (m^{-2} m^{-3}). Plots can be interpreted as a snapshot in time while the surface fire ignition interface is at $x = 0$. Baseline values for simulations and intermediate input values (not plotted in figure) are given in Table 1. Curves are truncated when T_f reaches 600 K.

MC also leads to a higher T_{Fmax} value and consequently an increase in the incident radiative energy flux to the canopy.

The two crown fuel variables defining the energy required for ignition, *FMC* and σ, showed the least effect on the predicted crown fuel particle temperature profile (Fig. 1*e*,*f*). *FMC* influences the energy required to ignite the fuel particle by increasing the average specific heat of the crown fuels (Albini 1985; de Mestre *et al*. 1989). Crown fuel particles are subjected to continuous and prolonged heating while the surface fire approaches and passes under their location (Alexander 1998). The change in energy required to ignite the fuel particle due to increases in *FMC* is comparatively small when compared to the cumulative energy flux absorbed by the fuel particles. This theoretical result corroborates the analysis of Cruz *et al*. (2004), which failed to find a statistically significant effect of *FMC* on the likelihood of crown fire occurrence based on field experiments. For the range of values tested, σ exhibited a negligible effect on crown fuel temperature and time to ignition.

Figure 2 displays the effect of the variation in the intermediate variables on the canopy fuel particle temperature profile. Surface fire *ROS* had the greatest effect on the predicted crown fuel particle temperature. *ROS* is a primary component in fireline intensity and flame depth determination, which subsequently influences flame height, air velocity in the buoyant plume, depth of the radiative surface, and diameter of the buoyant plume. This is shown by the sensitivity of both the convective and radiative energy fluxes (Fig. 3*a*,*b*) on *ROS*. A two-fold increase in the predicted *ROS* will double flame depth, and consequently double the size of the radiating surface and the width of the buoyant plume, causing increased energy transfer to crown fuel particles. However, as noted earlier, increases in *ROS* due to higher ambient wind speed do not necessarily directly increase crown fuel particle temperature as the plume may also be subjected to higher entrainment of cool air, leading to increased convective cooling of fuel particles.

Reaction time affects the size of the radiating surface and the buoyant plume initial width. As with *ROS*, higher τ_r results in an increase in the incident *E* to the lower canopy fuel particles and increases the depth of the buoyant plume. Over the ranges simulated, *ROS* and τ_r indicated roughly equivalent influence on incident radiative energy flux (Fig. 3*a*,*c*); with respect to convective energy flux, *ROS* had a greater effect (Fig. 3*b*,*d*).

Maximum flame temperature exhibited a lesser influence on crown fuel particle temperature than *ROS* and τ_r (Fig. 2*c*). T_{Fmax} impacts the surface fire T–T profile, leading

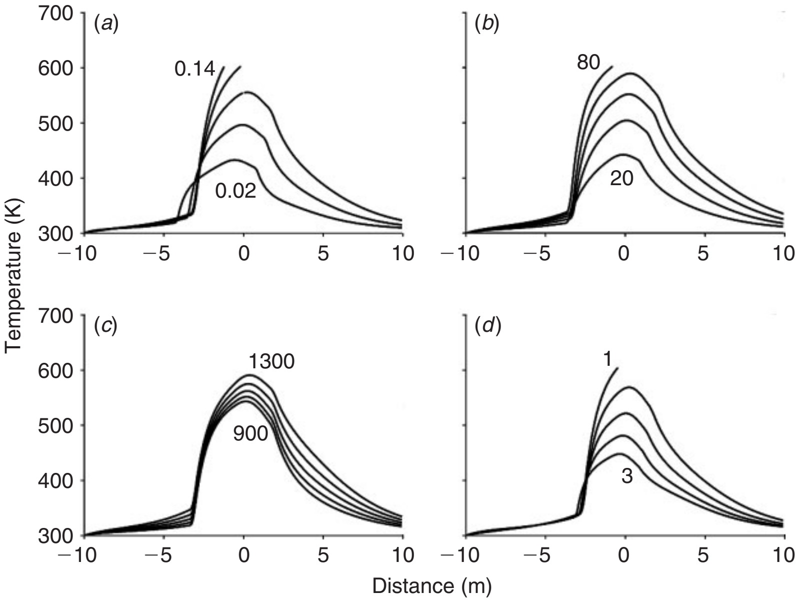

Fig. 2. Predicted temperature of lower canopy fuel particles above a spreading surface fire as a function of intermediate model outputs: (*a*) rate of spread ($m\ s^{-1}$); (*b*) reaction time (s); (*c*) maximum flame temperature (K); and (*d*) wind attenuation coefficient. Plots can be interpreted as a snapshot in time while the surface fire ignition interface is at $x = 0$. Baseline values for simulations and intermediate model output values (not plotted in figure) are given in Table 1.

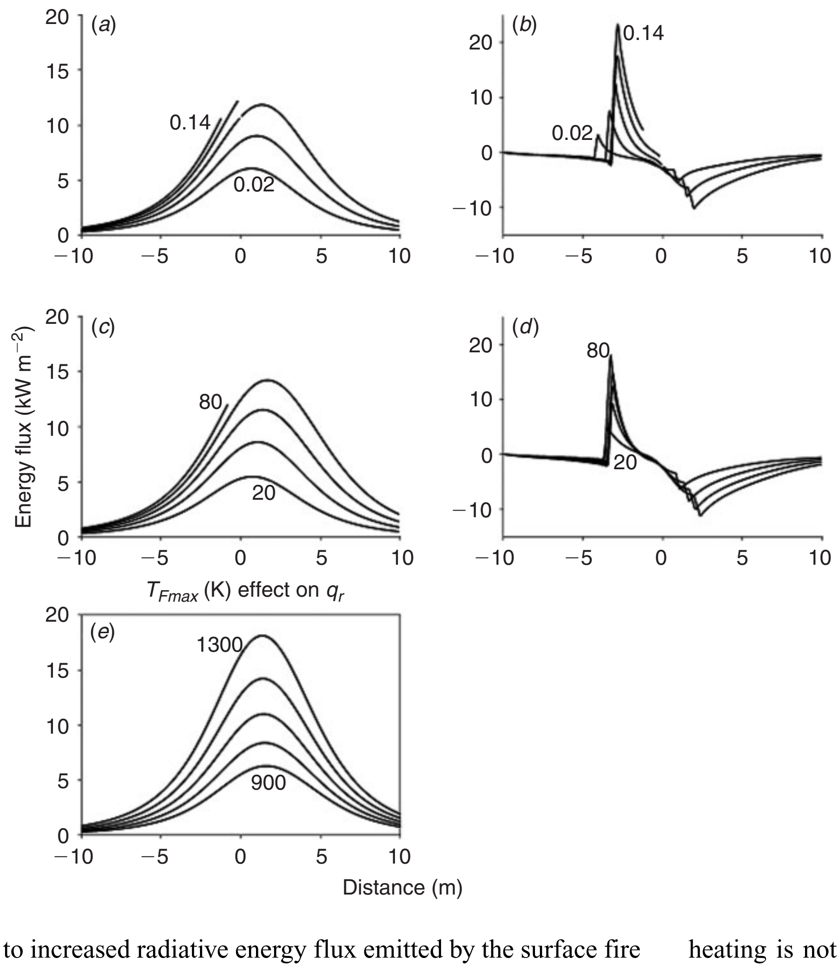

Fig. 3. Effect of intermediate model outputs on the convective and radiative energy flux reaching the base of the canopy fuels: (*a*) effect of rate of spread on the incident radiative energy flux; (*b*) effect of rate of spread on the convective heat flux; (*c*) effect of reaction time on the incident radiative energy flux; (*d*) effect of reaction time on the convective heat flux; and (*e*) effect of maximum flame temperature on the incident radiative energy flux. Plots can be interpreted as a snapshot in time while surface fire ignition interface is at $x = 0$. Baseline values for simulations are given in Table 1. Intermediate input values (not plotted in figure) are given on Table 1.

to increased radiative energy flux emitted by the surface fire (Fig. 3*e*). The occurrence of a high T_{Fmax} (e.g. 1300 K in Fig. 3*e*) results in a substantial increase in radiative heating after the passage of the leading edge of the flame front. For surface fires characterized by moderate to low T_{Fmax} radiative heating is not enough to counteract the convective cooling that occurs after the passage of the ignition interface. The effect of the wind attenuation coefficient (α_U) on the final model output is noteworthy (Fig. 2*d*). The wind attenuation coefficient determines the decay of wind speed with height within the forest stand. The effect of wind speed on the model system was discussed above.

Comparison with other models

The four crown fire initiation models under analysis showed distinct responses to fuel models and fuel moisture (Fig. 4). Of the four models tested the logistic model for crown fire occurrence (Cruz *et al.* 2004) tended to indicate crowning under the milder burning conditions, i.e. for a given *FSG* it indicated crown fire occurrence under lower U_{10} and higher *MC*. This model was also the least responsive to variations in the fire environment. The Van Wagner (1977) and Alexander (1998) models showed similar behavior, which reflects their similar conceptual formulation, i.e. attainment of a critical fireline intensity as the threshold for crowning. In terms of response to variations in burning conditions, Alexander's model displayed a higher responsivity than Van Wagner's. This could be somewhat expected as Alexander's model integrates a larger number of processes determining the initiation of crown fires, namely the surface fire reaction time, and the effect of the ambient wind in tilting and cooling the buoyant plume.

The results obtained for CFIM in Fig. 4 are encouraging as the model predictions qualitatively follow the behavior of the empirically based models and are consistent over a broad range of burning conditions. The U_{10} requirements for crown ignition using CFIM were higher than those required by the Cruz *et al.* (2004) model for all situations except the NFFL2 summer conditions. CFIM predictions fell between the Van Wagner (1977) and Alexander (1998) models for RPP and lower than the Van Wagner (1977) and Alexander (1998) models for NFF2. CFIM required the highest wind speeds for crowning for the surface fuelbed characteristics of NFFL10. The large differences in CFIM predictions between NFFL2 and NFFL10 are the result of the low spread potential of this fuel model. In fuel types characterized by low rates of surface fire spread, the development of a deep flaming front necessary to yield high convective and radiative energy fluxes to the crown fuels depends on the occurrence of strong wind speeds. Conversely, these high wind speeds reduce convective heat transfer to the crown fuels due to plume tilting and cool air mixing with the plume. Dieterich (1979) describes evidence of these mechanisms on the Burnt fire that occurred in the Coconino National Forest in northern Arizona on 2 November 1973. This run occurred predominately on open stands of ponderosa pine exhibiting low canopy base heights (1.2–1.5 m) under high wind velocities ($U_{10} = 74\,\mathrm{km\,h^{-1}}$) and relatively low estimated fine fuel moistures (9% as predicted by Rothermel [1983] fuel moisture tables). Although the estimated intensity was high, $5251\,\mathrm{kW\,m^{-1}}$ (Alexander 1998), postfire analysis revealed that crown damage varied from complete crown consumption in patches of saplings to large areas characterized by slight crown scorch 'on the lowest portions of the crowns' (Dieterich 1979).

An important question is the relative role of surface fuelbed structure and burning conditions (fuel moisture and wind) on the likelihood of crowning. Based on CFIM output, no definitive trend suggesting a dominance of fuel moisture and wind over surface fuelbed structure, or vice-versa, in inducing crowning could be identified. The RPP fuel model showed the largest variation in U_{10} required for crowning over the three standardized fuel moisture conditions tested (Fig. 4*a,d,g*). Conversely, model simulations based on NFFL10 result in moderate differences between fuel moisture conditions (Fig. 4*c,f,i*). Comparative analysis between RPP and NFFL10 shows small differences for the late spring conditions but large differences for the late summer conditions. This is believed to be the result of how surface fuelbed properties (structure and fuel moisture) affect the *ROS* predictions and how the parameters describing fuel consumption, both flaming and total, change throughout the burning season.

For the surface fuels tested, the model predictions showed the greatest variability under marginal burning conditions, e.g. late spring. For these conditions the Cruz *et al.* (2004) model was used outside of its original range of conditions. The model was unable to capture the effect that wetter burning conditions have on reducing surface fire spread and intensity. This might explain the discrepancies between this model and the trends yielded by other models. The high wind requirements for crown fire initiation needed by Alexander (1998) and CFIM for the RPP and NFFL10 fuel models for the 'late spring' conditions are believed to be the result of the effect of wind speed on plume behavior and fire intensity. Strong winds tend to dissipate the thermal plume but also result in increased *ROS* leading to increased fireline intensity (a critical value for Alexander's model) and deep flaming zones in CFIM. The simulations relying on the surface fuelbed description of RPP and NFFL2 for the 'late summer' burning conditions yield similar model results (Fig. 4*g,h*). A plausible explanation of this fact is that simulations were carried out under burning conditions analogous to the ones used on model development or that the models were exercised in a regime that was within that of sustained crown fire initiation.

Sensitivity analysis

Average sensitivity scores are given in Table 5. The results suggest a balanced model, with no variable having a disproportionate effect on the final model output. The convective heat transfer coefficient (h_c) was the variable showing the highest sensitivity to changes in the perturbed parameter, namely to U_{10} and w_a. Upward E showed slightly less sensitivity. In the CFIM model U_{10} and w_a have a strong effect on fireline intensity, which determines the initial air velocity in the buoyant plume. Results indicate that although the input variables analyzed perturb considerably both the h_c and E, the changes in T_f imply that the final model output is only slightly sensitive to changes in the most influential input variables.

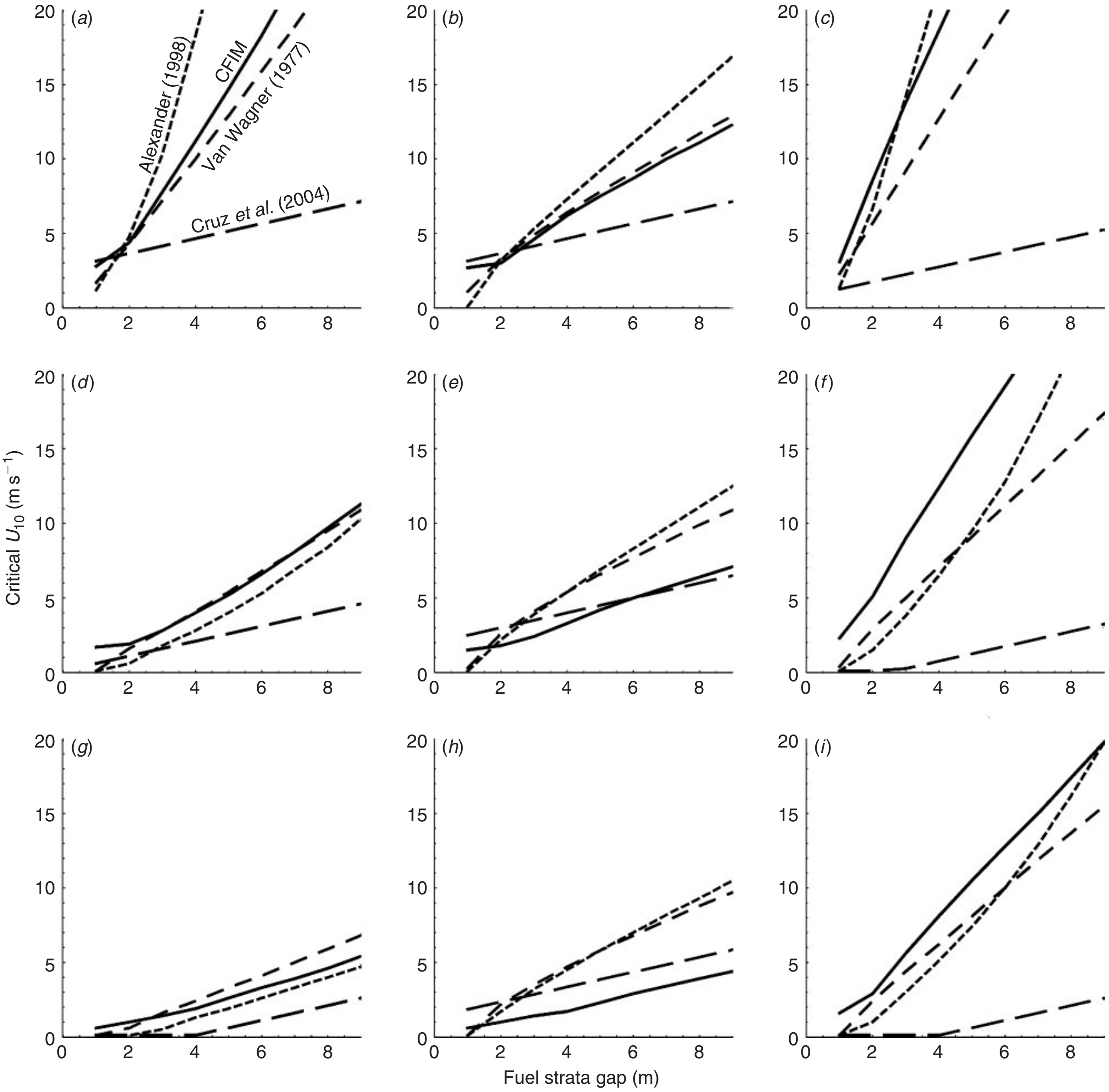

Fig. 4. Critical 10-m open wind speed for crown fire initiation as a function of fuel strata gap for Van Wagner (1977), Alexander (1998), Cruz *et al*. (2004), and CFIM. (*a*,*d*,*g*) Red pine fuel model; (*b*,*e*,*h*) NFFL2 fuel model; (*c*,*f*,*i*) NFFL10 fuel model. Fuel moisture characteristic of spring (*a*–*c*), normal summer (*d*–*f*), and late summer (*g*–*i*) are given in Table 2. Foliar moisture content = 1.2.

h_c and E sensitivity scores varied also with burning conditions. Variation of h_c *RS* scores suggests that the sensitivity of this parameter diminishes with an increase in the severity of burning conditions (e.g. higher U_{10} and/or w_a).

The results identify w_a as the variable causing the largest variation in the intermediate and final model output (Table 5). As indicated previously, w_a affects the model output by increasing fireline intensity and reaction time, leading to increased flame zone radiating surface size and buoyant plume diameter. Changes in *FSG* primarily affect h_c due to the dissipation of thermal energy and momentum in the plume with height. *MC* variation impacts the model by its effect on the *ROS* of the surface fire and the time temperature profile of the flaming zone.

Evaluation against experimental fire data

Overall, CFIM correctly predicted 14 of the 15 experimental fires (Table 6) although this result should be viewed with caution due to the uncertainty in estimating w_a on some of the fires. The number of fires used to evaluate CFIM was also small, restricting any possible inferences about model predictive capacity or bias. Nevertheless, the analysis of model behavior for some of the fires where detailed fire behavior information was available produced encouraging results. For both passive crown fires reported by Burrows *et al.* (1988) and (Fernandes *et al.* 2004), CFIM predicted crown combustion as occurring after the passage of the flaming front. In these simulations ignition temperature was attained while the contribution of convective heating was diminishing and the rate of increase in T_f was decreasing. These are borderline conditions relative to the occurrence of sustained crowning. In this situation the natural variation on fire environment conditions, such as wind speed or *FSG*, would result on a heterogeneous distribution of crowning activity, with only a fraction of the canopy fuel layer being consumed. This qualitatively agrees with the observed fire behavior. An exception is indicated in plot 8b (Stocks *et al.* 2004) where CFIM incorrectly indicated crown ignition. Nevertheless, a reduction of w_a to 0.75 kg m^{-2} for this fire results in a $T_f < 600$ K.

Table 5. Average sensitivity scores (standard deviation in parenthesis) of maximum crown fuel particle temperature (T_f), maximum air temperature in the buoyant plume (T_{air}), convective heat transfer coefficient, maximum (h_c), and surface fire upward radiant energy flux (E) to input variables

U_{10}, 10-m open wind speed; *FSG*, fuel strata gap; w_a, surface fuel available for flaming combustion; *MC*, moisture content of fine dead surface fuels

Input variables	T_f	T_{air}	h_c	E
U_{10}	0.35 (0.06)	0.36 (0.07)	1.85 (0.47)	0.15 (0.11)
FSG	0.07 (0.02)	0.07 (0.03)	0.21 (0.14)	–
w_a	0.45 (0.08)	0.44 (0.08)	1.13 (0.57)	0.44 (0.22)
MC	0.11 (0.05)	0.09 (0.06)	0.41 (0.28)	0.51 (0.1)

Conclusions

Cruz *et al.* (2006) described the structure of a model (CFIM) aimed at predicting the ignition of crown fuels above a spreading surface fire. The model was developed with the objective of providing a better understanding of the variables and processes determining the initiation of crown fires. CFIM quantifies the upward energy fluxes originating from a spreading surface fire and, in turn, calculates both the convective and radiative energy transfer to fuel particles located at the base of the canopy fuel layer. This model can be characterized as a hybrid model that combines fundamental heat transfer processes with empirically derived parameters. CFIM simplifies the description of certain fire processes, falling short of describing important fire phenomenology such as reaction zone processes and flame dynamics.

Model results suggest that the onset of crowning depends most on the mechanisms that determine the surface fire characteristics, namely reaction time, flame depth, and rate of energy release rather than on the physical characteristics of the canopy layer. The small effect that *FMC* has in the model is much smaller than assumed by other models (e.g. Van Wagner 1977), but agrees with the statistical results obtained by Cruz *et al.* (2004). A comparative analysis of the relative role of surface fuelbed structure and wind and fuel moisture conditions on the likelihood of crowning did not identify any superior role of these variables over surface fuelbed structure, or vice-versa, in inducing crowning. The results suggest that the relative role of these variables are not independent and that their effect varies with the fuel complex characteristics and burning conditions. The simulations indicate that some fuel types showed higher sensitivity to changes in burning conditions, implying a dominance of the role of

Table 6. Crown fire ignition model (CFIM) predictions for intermediate model outputs and crown base fuel temperature for experimental fires dataset

H_F, flame height; *FSG*, fuel strata gap; D_F, flame depth; τ_r, reaction time; b_{pi}, plume half width, initial; U_{pi}, plume velocity, initial; T_f, fuel temperature

Fire name	H_F (m)	*FSG*–H_F (m)	D_F (m)	τ_r (s)	b_{pi} (m)	U_{pi} (m s^{-1})	Max. T_f (K)	Crowing activity CFIM (Y/N)
VW67_R3	2.3	4.7	3.4	66	1.7	3.3	547	N
VW67_R4	1.1	5.9	2.3	65	1.1	2.8	392	N
VW67_R5	1.3	5.7	2.9	51	1.4	3.1	415	N
VW67_R1	2.9	4.1	6.2	57	3.1	3.9	>600	Y
BW&B_P1	1.8	0.6	3.8	77	1.9	3.4	>600	Y
BW&B_P2	1.9	0.5	4.3	77	2.2	3.5	>600	Y
BW&B_P3	1.7	0.7	3.3	75	1.6	3.2	>600	Y
McA66	1.9	8.1	6.9	104	3.4	4	490	N
VL&L_A2	1.4	0.4	2.1	55	1	2.8	>600	Y
VL&L_A4	0.9	0.9	0.88	52	0.44	2	492	N
VL&L_C2	0.3	1.5	0.53	53	0.26	1.7	398	N
PF&al_UN	2.1	2.6	5.9	98	2.9	4	>600	Y
PF&al_RX13	1.5	2.5	2.9	92	1.5	3.1	600	Y
PF&al_RX3	0.83	4.6	1.7	39	0.84	2.7	416	N
BS&al_Plot8b	1.6	3	4.5	48	2.2	3.8	>600	Y

climate/weather variables, while for other fuel types changes in burning condition severity were inconsequential on the likelihood of crowning.

Sensitivity analysis results suggest that the CFIM is well balanced. Over the natural range of their variability, no variable was found to have an overwhelming effect on sub-model components or on the final model output. CFIM predictions were within the range of the predictions made by the empirically based crown fire initiation models. For the simulations based on the use of fuel model NFFL10, CFIM was the most conservative of the models, i.e. required higher wind speeds to indicate crown ignition. This was attributed to the effect of the high wind speeds, which were required to develop a deep flame front, in tilting and cooling the buoyant plume. The evaluation of model behavior carried out in the present study hints at the adequacy of CFIM as a potential tool to be used to answer fire management questions. It is believed that the overall CFIM structure, incorporating important flame front phenomena and their interactions, results in a better description of the processes determining crown fire initiation than found in previously developed empirically based crown fire initiation models.

Model evaluation against an independent dataset from experimental fires provided encouraging results and gave insight into some limitations of the model system, namely the difficulty of correctly estimating some input variables. CFIM was applied to 15 experimental fire situations that included adequate descriptions of the fuel complex, weather conditions, and fire behavior characteristics. The model correctly predicted 14 of the 15 fires (eight surface and six passive crown fires) with respect to the ignition of crown fuels. The main difficulties in application of the CFIM against the independent experimental fire dataset resulted from the need to accurately estimate the available surface fuel for flaming combustion and to adequately describe the vertical wind profile. Surface fuelbeds are a complex array of live and dead fuels of differing size classes, displaying innumerable possible arrangements determined by compactness and relative proportions of the individual fuel particles. The physical structure of the surface fuelbed and associated burning conditions will largely determine the amount of fuel consumed in the flaming combustion phase. No objective method to estimate this quantity currently exists (Rothermel 1994). In the application of the CFIM to the experimental fire situations it was assumed for most of the fires that only the fine fuels, either live or dead, were consumed during the flaming combustion stage. Evidence from outdoor experimental fires (e.g. Van Wagner 1968) and laboratory fires (Cruz 2004) suggests that this assumption is not necessarily true, and substantial errors can be introduced as a result.

Although the results from the evaluation exercise are encouraging, the possible use of the model to predict fire behavior to support operational fire management activities should be preceded by additional evaluation of the model and familiarity of users to the model's structure, main underlying assumptions, and limitations. Additional evaluation should focus on the applicability of the model to specific fuel types. For example, an important question to answer is how particular surface fuel beds and burning conditions, as determined by fuel moisture variation by fuel particle type or layer, determine the surface fuel available for combustion in the active flame front, and consequently the reaction time. The range of possible surface fuelbed structures and resulting burning conditions is broad, and decisions relative to the best estimates of surface fuel available for flaming combustion should be complemented by the expert opinion of knowledgeable users with extensive operational experience in the particular fuel type of interest.

CFIM has the potential to be applied as a fire research tool. The balance between empiricism and fundamental energy transfer formulations allows the user to gain insights into the influence of certain fire environment variables and energy transfer processes on crown fire initiation. The CFIM system could be applied to problems related to the implications of fuel treatments and silvicultural operations in determining the resultant fire behavior potential. An example of this would be the analysis of stand treatments (e.g. distinctly different thinning methods), and subsequent changes in fuel complex characteristics and micrometeorology processes, on the susceptibility of the stand to initiate crown fire activity. By its structure, CFIM is expected to take into account many of the changes in the fire environment and in turn the resultant fire behavior induced by the treatment (e.g. higher within stand wind speed, increase or decrease in surface fire reaction time, changes in the buoyant plume characteristics) and thereby provide for an adequate description of the post-treatment potential for crown fire activity.

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